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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 3 : H04R 3/00, 3/08

A1

(11) International Publication Number: WO 84/ 00274

(43) International Publication Date: 19 January 1984 (19.01.84)

(21) International Application Number: PCT/GB83/00163

(22) International Filing Date: 29 June 1983 (29.06.83)

(31) Priority Application Number: 8218866

(32) Priority Date: 30 June 1982 (30.06.82)

(33) Priority Country: GB

(71) Applicant *(for all designated States except US):* B & W LOUDSPEAKERS LIMITED [GB/GB]; Meadow Road, Worthing, West Sussex BN11 2RX (GB).

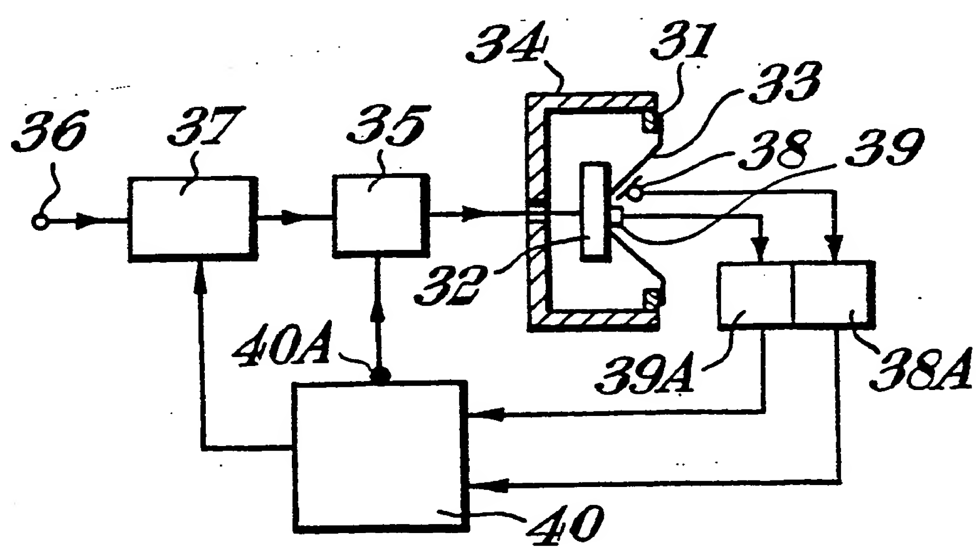
(72) Inventor; and
(75) Inventor/Applicant *(for US only)* : ADAMS, Glyn, John [GB/GB]; B & W Loudspeakers Limited, Meadow Road, Worthing, West Sussex BN11 2RX (GB).

(74) Agent: G.F. REDFERN & CO.; Marlborough Lodge, 14 Farncombe Road, Worthing, West Sussex BN11 2BT (GB).

(81) Designated States: AT (European patent), AU, BE (European patent), CH (European patent), DE (European patent), DK, FR (European patent), GB, GB (European patent), JP, LU (European patent), NL (European patent), NO, SE (European patent), US.

Published
With international search report.

(54) Title: ENVIRONMENT-ADAPTIVE LOUDSPEAKER SYSTEMS



(57) Abstract

High fidelity reproduction is adversely affected by normal room acoustics and the relative position of a loudspeaker system with respect to the room boundaries. To provide optimum results the invention proposes the use of pressure-sensing means (38) and velocity-sensing means (39) mounted to determine the instantaneous pressure and velocity at the surface of a loudspeaker diaphragm (33) and supply signals to a processor (40) which controls the transfer characteristic of a correction filter (37) via which input signals are fed to the loudspeaker.

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ENVIRONMENT-ADAPTIVE LOUDSPEAKER SYSTEMS

The invention relates to loudspeaker systems provided with a correcting filter in their input signal circuit to provide required characteristics.

The most common type of loudspeaker system used today takes the form of one or more direct-radiator moving-coil loudspeaker drivers mounted into a closed box or enclosure. Here the diaphragm of each moving-coil driver radiates directly into the sound field as opposed to other types which have some additional acoustic device (such as a horn) inserted between the source and the field.

The acoustic power radiated into the sound field by the direct-radiator loudspeaker system is a function of the velocity distribution over the surface(s) of the moving diaphragm(s) and the radiation impedance load of the air presented to the outer surface(s) of the diaphragm(s).

The radiated acoustic power is also a function of both the position of the system relative to the room boundaries and of the resonance modes of the room.

Many of the problems impeding high fidelity reproduction can be solved by component design for the middle and high frequencies, but the room properties are most significant in the low frequency region, and specific design of room acoustics and the position of

the system and the listener become critical. Attempts to produce a correction signal by a monitoring microphone can only be successful for a given listening position.

In the case of a single rigid loudspeaker diaphragm of effective radius <u>a</u>, mounted in a sealed enclosure, if we consider sinusoidal motion of the loudspeaker diaphragm, and let the rms value of the diaphragm velocity be V, then the power W radiated into the far field is given by :-

$$W = R_r V^2 \quad , \qquad (1)$$

where R_r is the resistive part of the mechanical radiation load presented to the exposed front surface of the diaphragm, and for a given value of V, the acoustic power radiated is a direct function of the radiation resistance R_r.

However, the radiation load has a reactive component, the radiation reactance X_r. For frequencies where the wavelength of sound in air is greater than the circumference of the driver diaphragm (i.e. for $ka < 1$ where $k = 2\pi f/c$, f is the frequency and c is the velocity of sound in air) the radiation load is predominantly reactive as described by O. Jacobsen, in an article entitled:- "Some Aspects of the Self and Mutual Radiation Impedance Concept with Respect to Loudspeakers", J. Audio Eng. Soc., vol. 24, pp. 82-92 (Mar. 1976). The reactive part can be thought of as being a result of the mechanical impedance load

presented to the diaphragm by the mass of the air in the vicinity of the front of the driver diaphragm. Indeed for a driver mounted in an infinite baffle, the calculated value of this air mass is approximately equal to the mass of an imaginary cylinder of the medium having the same radius as the driver diaphragm and a length of $8\underline{a}/3\pi$, as described by L.E. Kinsler and A.R. Frey, in their work entitled "Fundamentals of Acoustics" (Wiley, 1962).

The radiation resistance changes when the loudspeaker system is placed near room boundaries or any object which is large compared to the wavelength of sound in air. Also, the radiation resistance will change at frequencies where standing waves are set up in a room in which the loudspeaker system is placed.

At low frequencies it is desirable to radiate the same power level at all frequencies for the same input signal voltage applied to the loudspeaker system. From the foregoing discussion it is clear that the radiated sound power is a function of the environment in which the loudspeaker system is placed. Thus with conventional loudspeakers a uniform power/frequency response at low frequencies is not obtained in general.

One object of the present invention is to provide an environment-adaptive loudspeaker system which enables these problems to be overcome or

significantly reduced.

In accordance with the present invention there is provided an environment-adaptive loudspeaker system comprising a direct radiator moving-coil loudspeaker system connected to an input signal voltage source via a series combination of a correction filter and a power amplifier, pressure-sensing means mounted to produce a first signal indicating pressure variations on or closely adjacent the loudspeaker diaphragm, velocity sensing means mounted to produce a second signal indicating diaphragm velocity variations, means for producing from said first and said second signals a control signal dependent upon the phase angle of the radiation impedance, which control signal is applied to vary the characteristic of said correction filter in order to minimise any adverse effect of the environment.

The invention will now be described with reference to the drawings, in which:-

Figure 1 is a theoretical equivalent circuit diagram for use in explaining the radiation load presented to the front side of a loudspeaker diaphragm;

Figure 2 is an explanatory vector diagram; and

Figure 3 is a block schematic circuit diagram illustrating one exemplary embodiment of a system constructed in accordance with the invention.

With a typical direct-radiator loudspeaker used as the driver, the magnitude of the radiation load presented to the diaphragm at low frequencies is small compared to the mechanical impedance of the diaphragm assembly itself. Variations in the magnitude of the radiation load as a function of the environment about the loudspeaker system are also found to be small, as shown by the relative independence of the sound-pressure amplitude measured as a function of the environment just above the diaphragm surface. Thus for a given input voltage applied to the voice coil of the driver, the velocity of the diaphragm will be independent of the radiation load presented to the diaphragm.

The simplified theoretical circuit shown in Figure 1 represents an analogous model of the radiation mechanism for a direct-radiator moving-coil loudspeaker driver having an effective diaphragm radius $\underline{a}$ and an instantaneous velocity $\underline{v}$, represented by a current source to render it independent of the load. The radiation impedance Z_r is represented by $Z_r = R_r + jX_r$;

Where R_r is the radiation resistance; and

X_r is the radiation reactance.

The voltage across the radiation impedance is equal to the reaction force which the diaphragm experiences against the medium. For low frequencies, i.e., where $\underline{ka} < 1$, the sound-pressure distribution

over the diaphragm surface is essentially uniform and thus the instantaneous reaction force can be expressed as the product of the effective diaphragm area and the instantaneous sound pressure p on (or just above) the diaphragm surface.

Figure 2 shows that the magnitude of the radiation impedance $|Z_r|$ is given by $\sqrt{R_r^2 + X_r^2}$ and that the phase angle ϕ of the radiation impedance is given by $\cos\phi = R_r/|Z_r|$. If the rms value of a sinusoidal variation in p is denoted P, then by definition:-

$$|Z_r| = \text{rms force/rms velocity} = P\pi a^2/V \qquad (2)$$

Equation (1) can now be written:-

$$W = \frac{P\pi a^2}{V} \cos\phi \; V^2, \text{ to obtain:-}$$

$$W = PV \cos\phi \, \pi a^2 \qquad (3)$$

The acoustic power radiated is thus proportional to the product of the magnitudes of the velocity of the diaphragm surface and the sound pressure on the diaphragm surface multiplied by the cosine of the phase angle of the radiation load. Equation (3) can be compared to the power in an electrical load, VI $\cos\phi$. In electrical engineering terminology, $\cos\phi$ is described as the power factor of the load.

If the pressure and velocity distributions on the diaphragm surface are not uniform (as would be the case if the diaphragm were exhibiting bending and/or if $ka > 1$) then equation (3) becomes

$$W = \int_{\substack{\text{Diaphragm} \\ \text{Surface}}} P.V.\cos\phi.\underline{ds} \qquad (4)$$

where $\underline{ds}$ is an elemental area on the diaphragm surface and P, V and $\cos\phi$ are functions of the position of $\underline{ds}$ on the surface.

For low frequencies, where $X_r \gg R_r$, the phase angle ϕ is near to 90^{o} and thus the power factor is close to zero. The magnitude of X_r is largely independent of the room environment and therefore $\cos\phi$ is directly proportional to R_r at any given frequency (see Fig. 2), so it is this term in equation (3) which mainly accounts for the influence of the room environment on the acoustic power radiated.

Because R_r is small compared to X_r, variations of its value have little effect on the values of P and V but a significant effect on the value of $\cos\phi$. Variations in the magnitude of P as a function of the environment can be several dB in practice, and both P and $\cos\phi$ should be measured for determination of the acoustic power output.

For low frequencies, where $\underline{ka} < 1$ and the driver diaphragm remains rigid, the pressure and velocity distribution on the diaphragm surface are essentially uniform. In these circumstances, the pressure and velocity values in equation (3) can be measured at any one convenient point on the diaphragm surface. By removing the cloth dust cap from the diaphragm of a

30-cm diameter driver and replacing it with a hard circular disc having a subminiature accelerometer and a subminiature electret microphone attached, the signal from the accelerometer can be used to determine the diaphragm velocity, whilst the low-frequency response of the simple electret microphone, carefully equalised, gives a frequency response comparable to that obtained from a sophisticated microphone positioned just above the circular disc. The measured amplitudes of the acceleration and equalised pressure signals as a function of frequency, with the driver mounted in a sealed enclosure of $100dm^3$ in volume and placed in an anechoic chamber give acceleration and pressure curves that overlay within 0.5 dB between 10 Hz and 200 Hz; above 200 Hz the acceleration curve departs from the pressure curve because of cone flexure. Thus above 200 Hz the pressure and acceleration signals are not valid for the computation of acoustic power output. The upper limit could be extended by using a driver of smaller diameter, or by employing an array of sensors. The phase difference measured between the pressure and acceleration signals for the loudspeaker system in an anechoic environment shows that the phase angle (i.e., 90-ø) varies between about 3 and 8 degrees, i.e., ø varies between about 87 and 82 degrees, the radiation impedance being mainly reactive.

If the measurements are repeated with the

loudspeaker positioned in the corner of a normal room, the phase angle ø shows much larger variations - between about 60 and 88 degrees. Peaks in the power factor are indicative of increases in the power radiated at those resonance frequencies of the room which are excited by the loudspeaker. The power factor of the radiation load is reduced between 120 and 150 Hz compared to the anechoic load. This corresponds to a trough in the power-output/frequency response of about 5 dB. Troughs of this type are described by R.F. Allison in "The Influence of Room Boundaries on Loudspeaker Power Output", J. Audio Eng. Soc., vol.22, pp.314-320 (June 1974). The pressure response shows variations of up to about 2 dB compared to the anechoic case. This variation is obviously worth taking account of in the calculation of the power output for different environments, but it is clearly not as important as the variation of the power factor of the acoustic load.

The acceleration curve closely follows the course of that measured under anechoic conditions, as would be expected. Values for power factors at frequencies between 20 and 200 Hz can be computed from experimental results, and six or seven peaks of up to 5dB appear in the band from 20 to 100 Hz, before the above-mentioned trough.

In the embodiment of the invention illustrated in Figure 3 a moving-coil loudspeaker 31, with a drive

coil (not shown) and a permanent magnet assembly 32 coupled to drive a diaphragm 33, is mounted in a speaker housing 34, which in this case does not include any vents or ports other than an aperture over which the diaphragm 33 is fitted. A power amplifier 35 is provided to feed signals to the drive coil, the input of this amplifier 35 being connected to an input signal terminal 36 via a controllable correction filter 37. To sense the pressure, in this embodiment a single microphone 38 is fitted closely adjacent the diaphragm 33. To sense the velocity of the diaphragm a single transducer 39, in this case an accelerometer, is attached to the central part of the diaphragm 33. The signal outputs from the sensing means 38 and 39 are fed to respective sensor amplifiers 38A and 39A, which feed signals to a processor 40. The signals are of analogue form in this embodiment, but a conversion to a digital format may be effected if the processor 40 is of a type operating in a digital mode.

The processor 40 is designed to produce a control signal from the applied sensor signals, and feeds this control signal to the correction filter 37, in order to vary its amplitude/frequency transmission characteristics in a predetermined manner dependent upon the sensor signals.

Thus, instead of introducing compensation for the sound-pressure response at a single listening

position, compensation derived from single sensors at the loud speaker are introduced to make the acoustic power-output/frequency response of the system uniform substantially throughout the listening room.

For those frequencies, where the velocity distribution is substantially uniform over the diaphragm surface, the velocity can be sensed by a single accelerometer attached to the diaphragm. Also for such frequencies, as the pressure distribution does not undergo wide level variations over the diaphragm surface, the pressure can be sensed by a single microphone positioned centrally on or just above the diaphragm surface.

Up to this point the operation of the system has only been considered at those frequencies where the wavelength of sound in air is greater than the circumference of the driver diaphragm. For these frequencies the pressure and velocity distributions are substantially uniform over the diaphragm surface, thus enabling the use of a single pressure sensor and a single velocity sensor to suffice. At higher frequencies, where these distributions are no longer uniform, a multiplicity of pressure and velocity sensors needs to be provided, each distributed over the diaphragm surface. The signals from these sensors can be combined in such a way that a correction signal proportional to the radiation resistance can be obtained, and used to define the required transfer

function of the correction filter.

The processor circuit in the illustrated embodiment is required to compute the value of cos ϕ as a function of frequency and then adjust the frequency response of the correction filter in such a way that the desired sound power-output/frequency response is obtained.

If the power-output/frequency response is required to be independent of frequency, the correction filter response would be such that large amplitude excursions of the diaphragm would occur at frequencies below the fundamental resonance of the system. This is because the magnitudes of both P and V fall off with decreasing frequency, below resonance. A more practical specification of the desired sound-power/frequency response would be that it should remain the same as that obtained when the loudspeaker system is radiating into a completely free space (i.e. into a free field).

The correction filter 37 can be an electronic digital filter whose frequency response is defined by digital output signals from the processor 40. The latter can take the form of an inexpensive digital micro-computer with analogue signal inputs for the pressure and velocity signals, and suitable analogue-to-digital converters. Alternatively, an analogue mode correction filter could be used, such as a switched-capacitor filter, or a transversal filter,

operating under the control of digital signals from the processor 40, or the processor can be programmed to feed an analogue correction signal into an appropriately designed correction filter. The processor can be designed to compute the required transfer function from the pressure and velocity signals, relevant values of cos Ø being stored permanently in the micro-computers memory store after being derived from measurements carried out in a free-field environment.

To facilitate the computation of the transfer function an analogue test signal output 40A from the processor 40 can be provided to feed a test waveform of varying frequency to drive the loudspeaker via the power amplifier 35 each time the system is switched on. The processor 40 can then compute the required transfer function from the pressure and velocity data collected during the test, which will be correct for the environment then existing.

Thus, if the filter is required to be self-adaptive, the requisite correction is automatically adjusted when the loudspeaker system is moved from one environment to another, the processor being arranged in such a way that the correction filter is automatically re-programmed whenever the system is switched on. Each newly measured power-output/frequency response is compared with a stored power output curve previously selected as the most desirable

characteristic.

Another advantage of the system proposed in accordance with the invention is that the pressure and/or velocity signals from the sensors can be used to apply motional feedback to the system with the addition of very little extra circuitry.

The invention can be applied to each individual channel of a multi-channel system, be it stereophonic, quadrophonic or the like, and can also be used for individual loudspeakers of a multi-unit assembly including different direct radiators for two or more mutually different frequency ranges.

CLAIMS:-

1. An environment-adaptive loudspeaker system comprising a direct radiator moving-coil loudspeaker system connected to an input signal voltage source via a series combination of a correction filter and a power amplifier, pressure-sensing means mounted to produce a first signal indicating pressure variations on or closely adjacent the loudspeaker diaphragm, velocity sensing means mounted to produce a second signal indicating diaphragm velocity variations, means for producing from said first and said second signals a control signal dependent upon the phase angle of the radiation impedance, which control signal is applied to vary the characteristic of said correction filter in order to minimise any adverse effect of the environment.

2. A system as claimed in Claim 1, in which said moving-coil loudspeaker system comprises a housing having a single aperture which is closed by a diaphragm of a single loudspeaker.

3. A system as claimed in Claim 1 or Claim 2, in which said pressure-sensing means is a microphone.

4. A system as claimed in Claim 1 or Claim 2, in which said velocity sensing means is an accelerometer.

5. A system as claimed in Claim 1, in which said

pressure-sensing means comprises a plurality of microphones positioned in an array in close proximity to the surface of said loudspeaker diaphragm.

6. A system as claimed in Claim 1, in which said velocity sensing means comprises a plurality of accelerometers.

7. A system as claimed in Claim 1, in which said control signal is applied to said correction filter as an analogue signal.

8. A system as claimed in Claim 1, in which said control signal is applied to said correction filter as a digital signal.

9. A system as claimed in Claim 1, in which said correction filter includes storage means for holding a predetermined power-output/frequency response curve, test means for transmitting a test waveform via said loudspeaker when said system is switched on, and comparator means for comparing the response produced by said test waveform transmission with the stored response curve to derive the requisite control signal.

10. An environment-adaptive loudspeaker system substantially as described with reference to Figure 3.

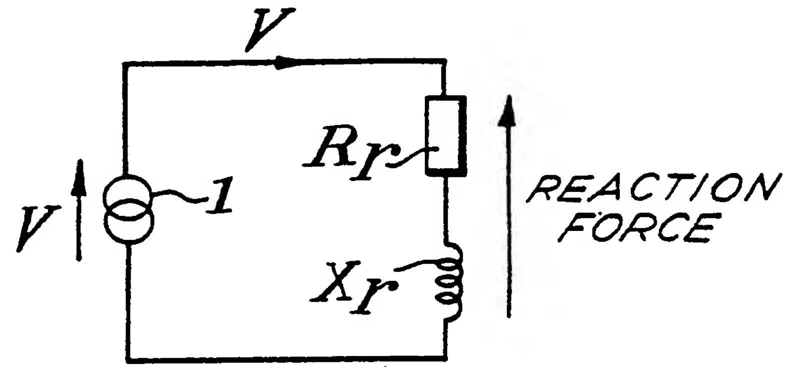

Fig.1

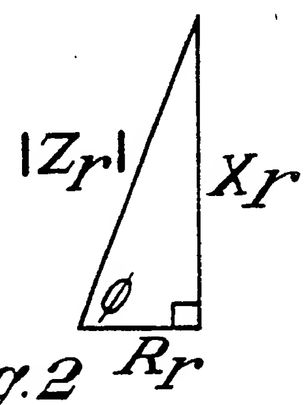

Fig.2

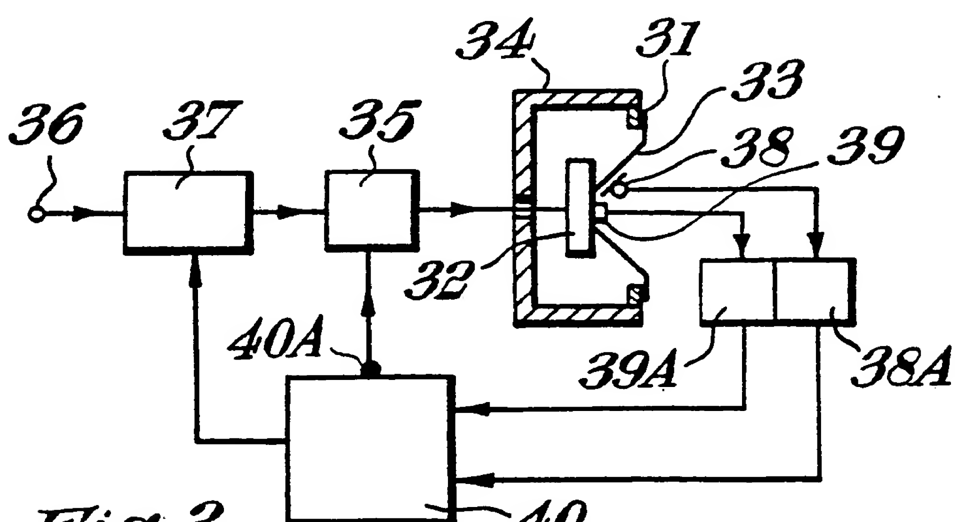

Fig.3

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 83/00163

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^3: H 04 R 3/00; H 04 R 3/08

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
IPC^3	H 04 R

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
Y	DE, A, 2141141 (NEUMANN) 22 February 1973 see page 5, line 1 - page 8, line 12; claim 4	1,3,5
	--	
Y	GB, A, 2068678 (DBX) 12 August 1981 see page 2, line 20 - page 5, line 129; page 6, line 119 - page 7, line 36	1,3,5
A		8,9
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A	DE, A, 2617888 (TELEDYNE) 4 November 1976 see page 3, lines 11-19; page 5, line 18 - page 7, line 8	1,7
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A	US, A, 4306113 (MORTON) 15 December 1981	1,3,8,9 ./.

* Special categories of cited documents: [15]

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IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
28th September 1983	20 OCT. 1983
International Searching Authority [1]	**Signature of Authorized Officer** [20]
EUROPEAN PATENT OFFICE	G.L.M. Kruydenberg

Form PCT/ISA/210 (second sheet) (October 1981)

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, 16 with indication, where appropriate, of the relevant passages 17	Relevant to Claim No 18
	see the entire document --	
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A	US, A, 3889060 (GOTO et al.) 10 June 1975 see column 2, lines 60-66; column 4, line 37 - column 6, line 32 --	1,3,4
A	DE, A, 2538073 (HILGERS) 10 March 1977 see page 2, line 15 - page 3, line 30 --	1,4
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A	DE, A, 2637414 (SIEMENS) 23 February 1978 see page 7, line 38 - page 8, line 26 --	2
A	Electronics, vol. 36, no. 18, 3 May 1963 (New York, US) Gray: "Consumer Electronics", pages 49-54, see page 54, right-hand column, lines 28-31 ------	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO. PCT/GB 83/00163 (SA 5452)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 14/10/83

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		JP-A-	50040124	12/04/75
DE-A- 2538073	10/03/77	None		
DE-A- 2626652	22/12/77	None		
DE-A- 2637414	23/02/78	None		

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82